21cm Intensity Mapping

a progress report

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on behalf of

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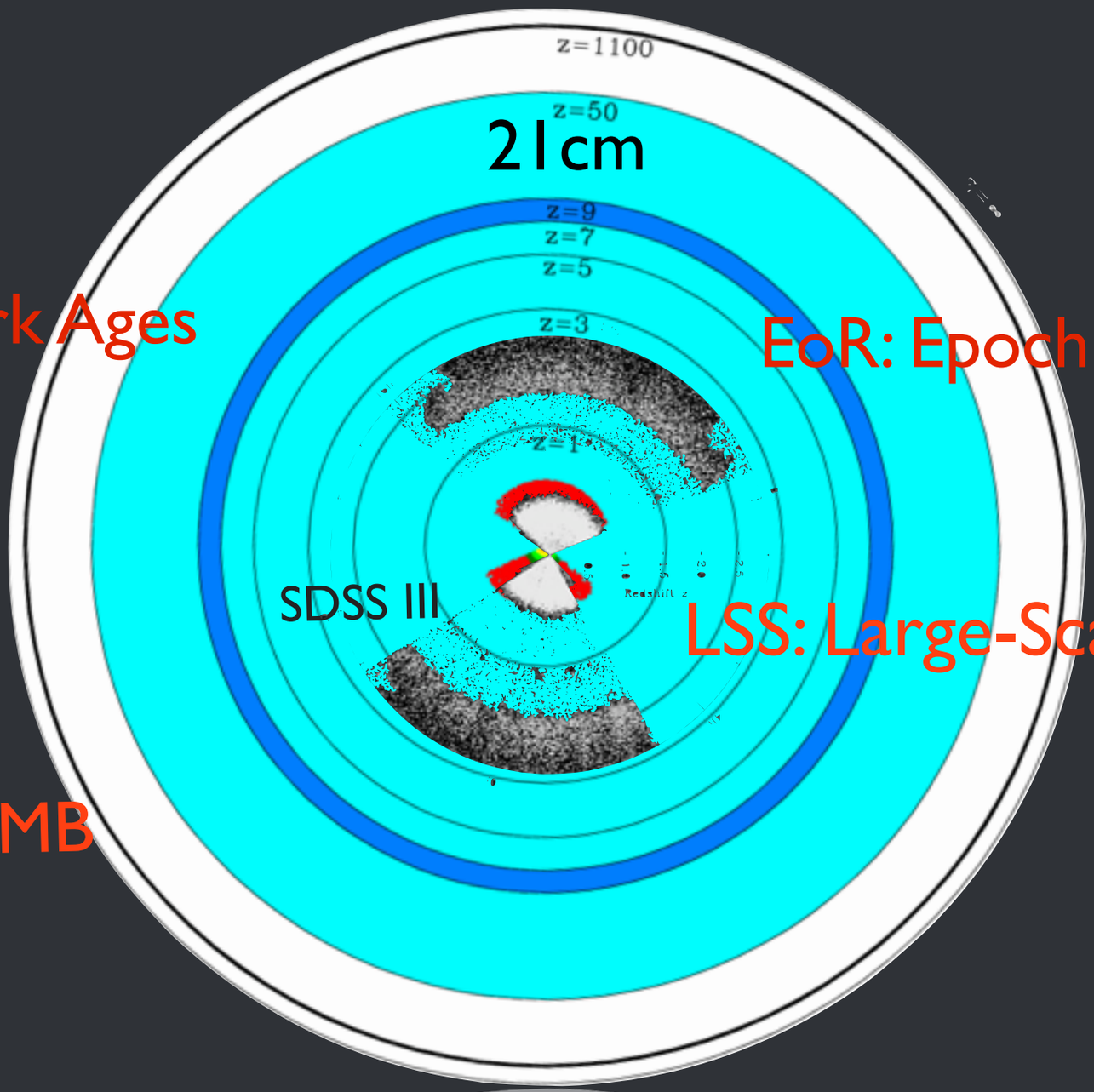
Yuh-Jing Hwang, Ching-Ting Ho, Chi-Chang Lin(ASIAA)
Rich Bradley, John Ford, Sri Srikanth, Steve White (NRAO)

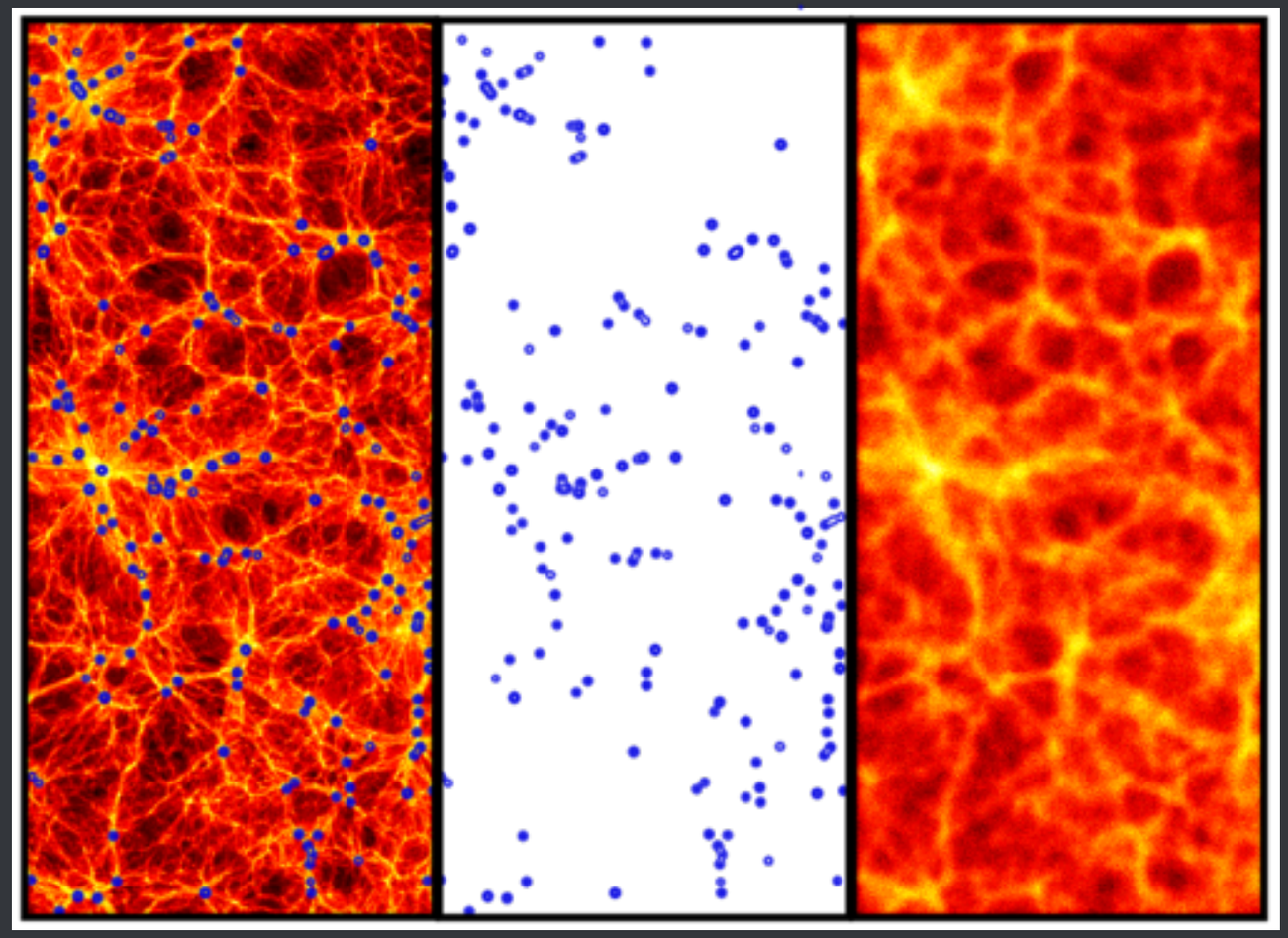
21cm Cosmology



- potential to map out all accessible modes to z~150

derived from Mao et al. 08;
Tegmark & Zaldarriaga 09

21cm Intensity Mapping



courtesy of Phil Krongut (Caltech)

- "Intensity Mapping" (Chang, Pen+ 2008, Wyithe & Loeb 2008):

  - Measure the collective emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.

  - Retain high frequency resolution thus redshift information

  - Brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D

  - Low-angular resolution redshift surveys: LSS sciences, economical

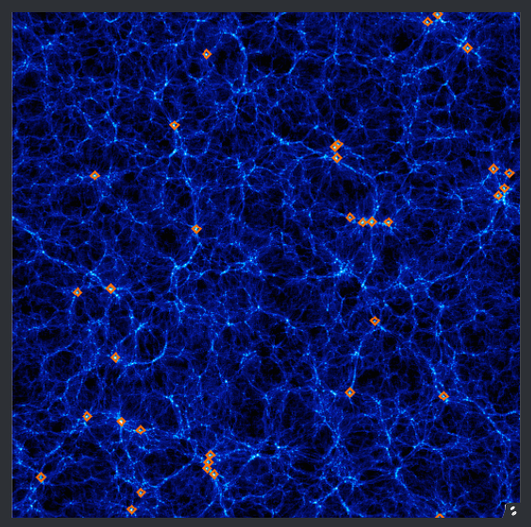
  - Confusion-limited. Foreground-limited.

Current 21cm Intensity Mapping Efforts

Intensity mapping: low-resolution, not resolving individual sources, CMB-like, in 3D

1 → 10 → z

LSS; BAO

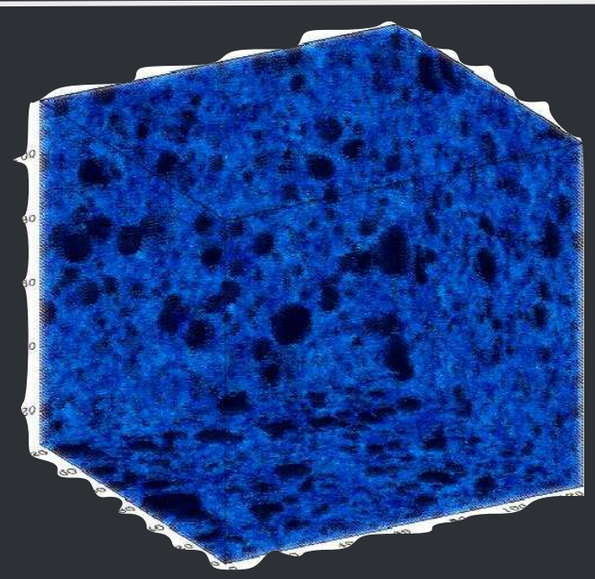


M. White

- 0.5<z<2.5, HI traces underlying matter distribution, can be used to measure Baryon Acoustic Oscillations (BAO), 109 h^{-1} Mpc scale => dark energy

- CHIME, Tianlai, HIRAX, GBT-HIM, SKA1-MID

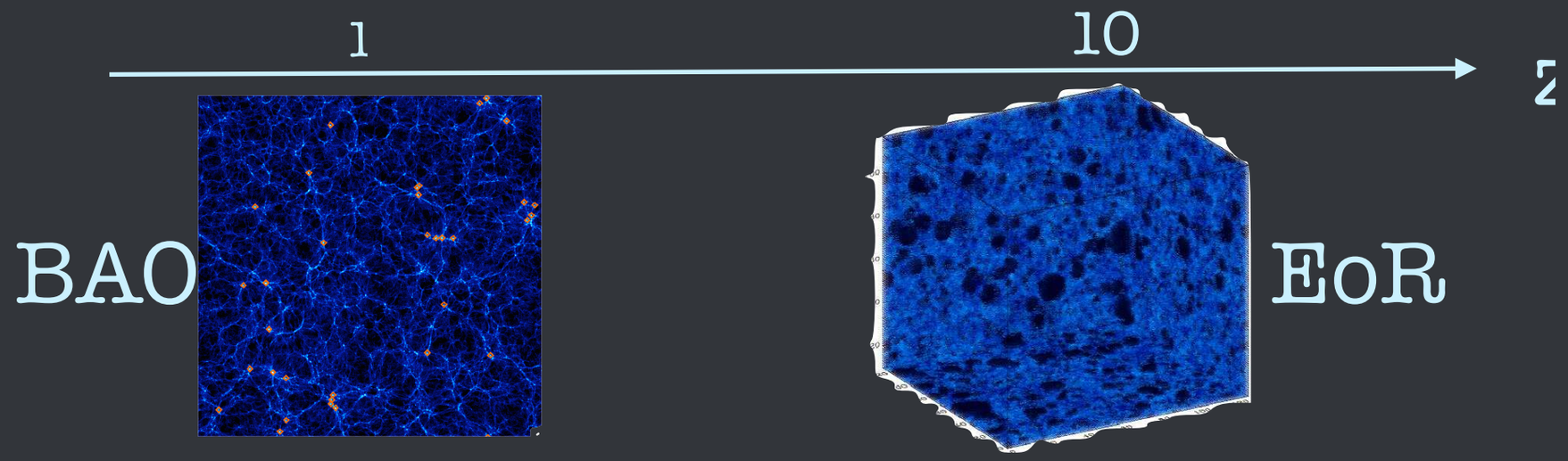
EoR



- 6<z<10, Epoch of Reionization (EoR), HI shows tomographic history of reionization, ~20-50 Mpc scale => astrophysics

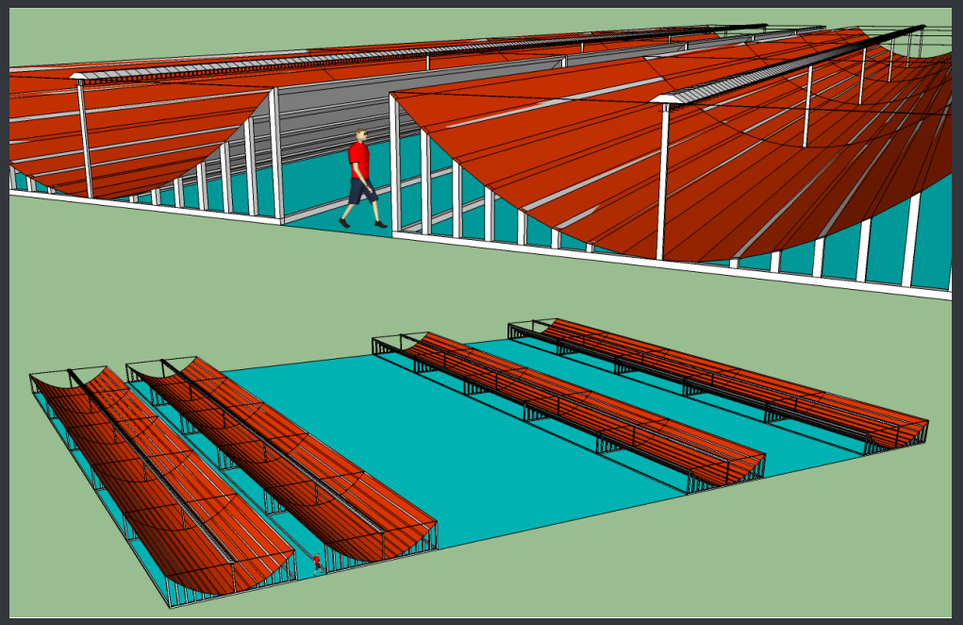
- LOFAR, PAPER, MWA, GMRT-EoR, HERA, SKA1-LOW

Observing 21cm Large-Scale Structure



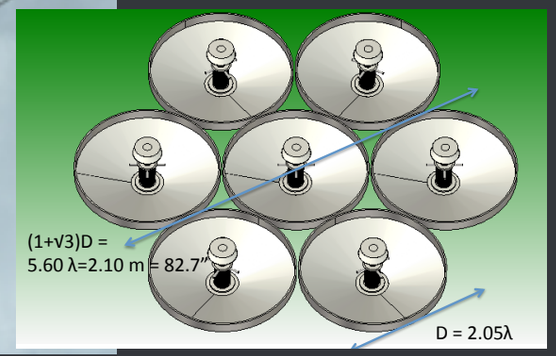
z	~1	~10
Science goal	Large-scale structure; BAO,RSD	Cosmic Reionization
Signal (mK)	0.1	10
Tsys (K)	30	300
Foreground spatial fluctuation (K)	0.1	10
Size scale	~10' - 1.4 deg; 109 h (non-linear scale - first peak)	~10'-30'; 20-50 Mpc (bubble scale)
First proposed	~2007	1970's?
Strategy	single dish; Interferometers	Interferometers
	cross-correlations possible now!	

Low-z 21cm Intensity Mapping Experiments

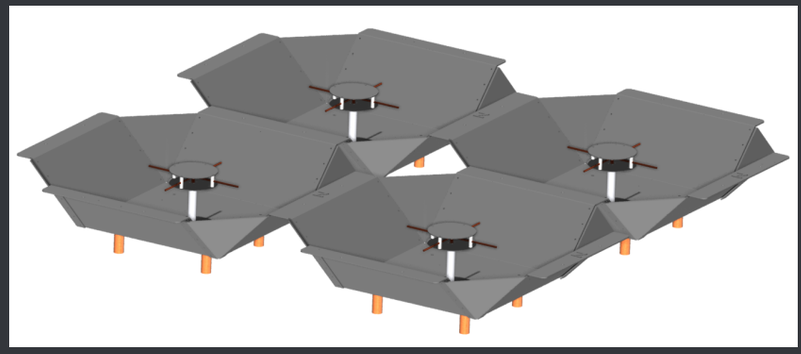


CHIME/Tian-Lai/CRT/BAORadio

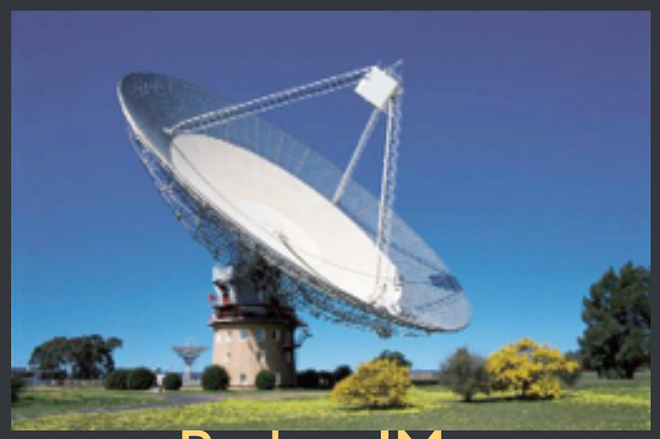
GBT-HIM multi-beam



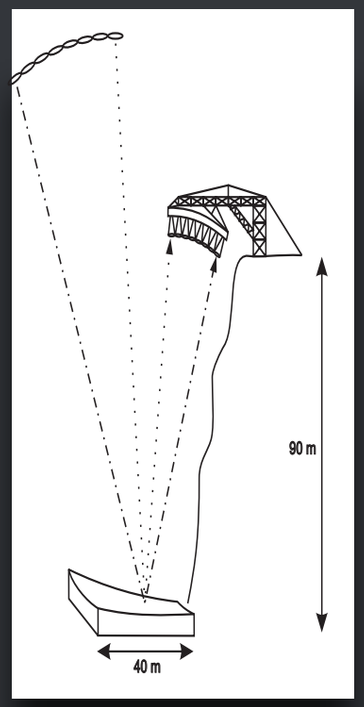
HIRAX



BAOBAB



Parkes IM

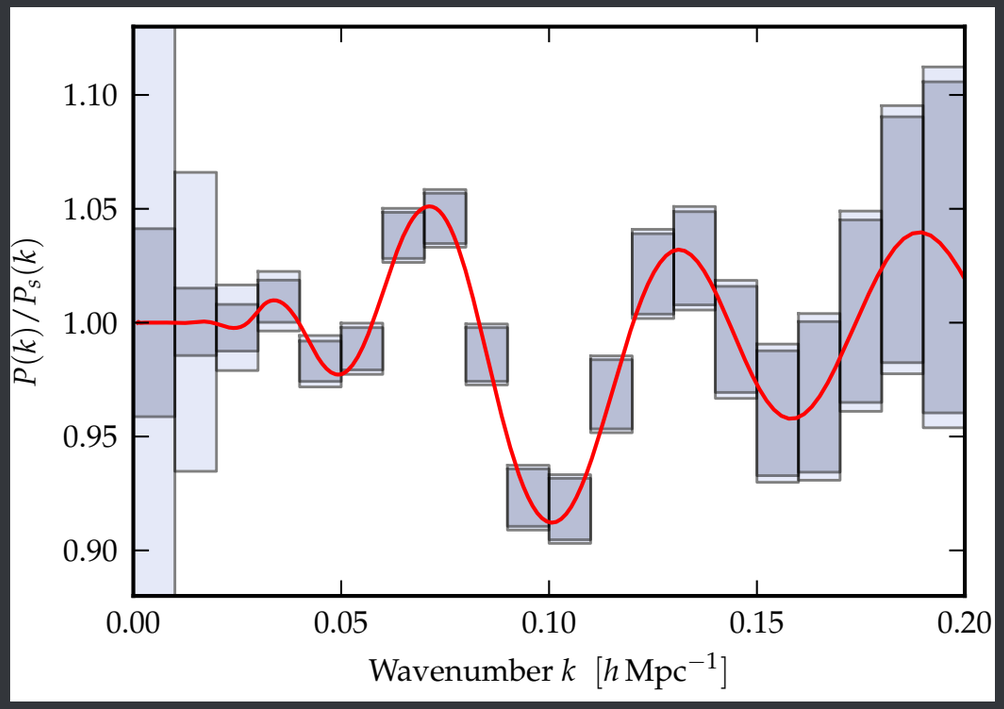


BINGO

SKA-mid Telescope

Cosmological Implications

- Baryon Acoustic Oscillation, Redshift-space distortion measurements
- Constrain dark energy equation of state and its running



Shaw et al. 2014

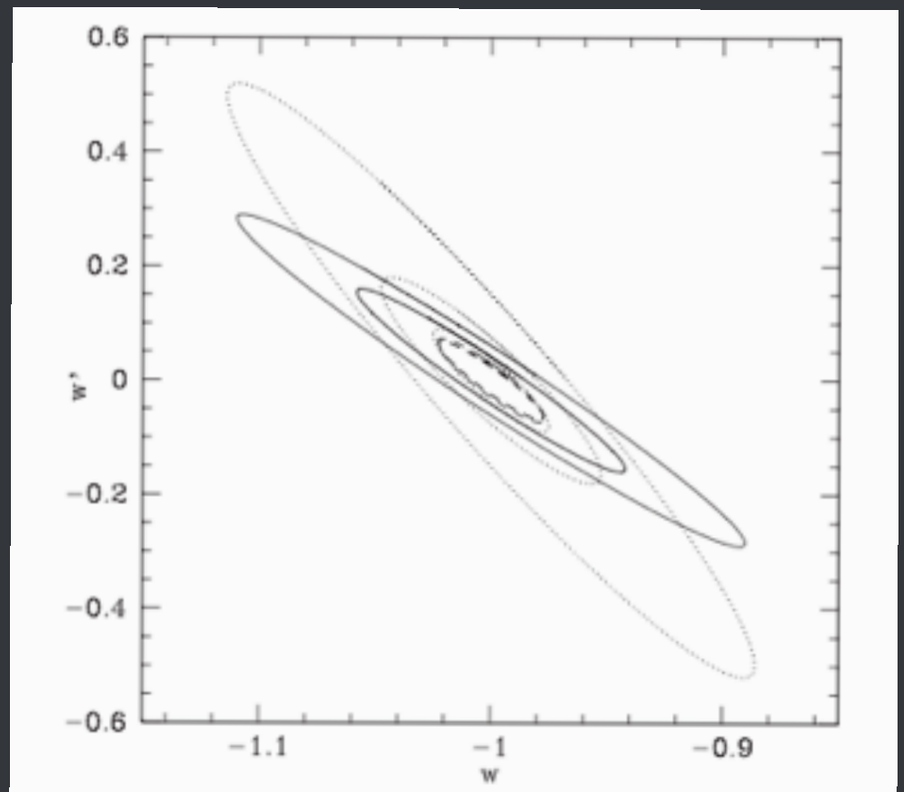


FIG. 4. The $1-\sigma$ contour for IM combined with Planck (inner thick solid for baseline model, outer thin solid for worst case), the Dark Energy Task Force stage I projects with Planck (outer dotted), the stage I and III projects with Planck (intermediate dotted), the stage I, III, and IV projects with Planck (inner dotted), and all above experiments combined (dashed, again thick for baseline, thin for worst case; the two contours are nearly indistinguishable).

Chang et al. 2008

GBT-HIM

Pilot program at the Green Bank Telescope (GBT)

- Frequency: 700-900 MHz
  - 0.6 < z < 1
- Spatial beam ~ 15”
  - 9 h^{-1} Mpc at z~0.8
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 h^{-1} Mpc
- 100-m diameter. Large collecting areas
- First detection in cross-correlation with DEEP2 galaxies at z=0.8 (Chang, Pen, Bandura, Peterson, 2010, Nature)

21cm Intensity Mapping at the GBT

- Frequency: 700-900 MHz
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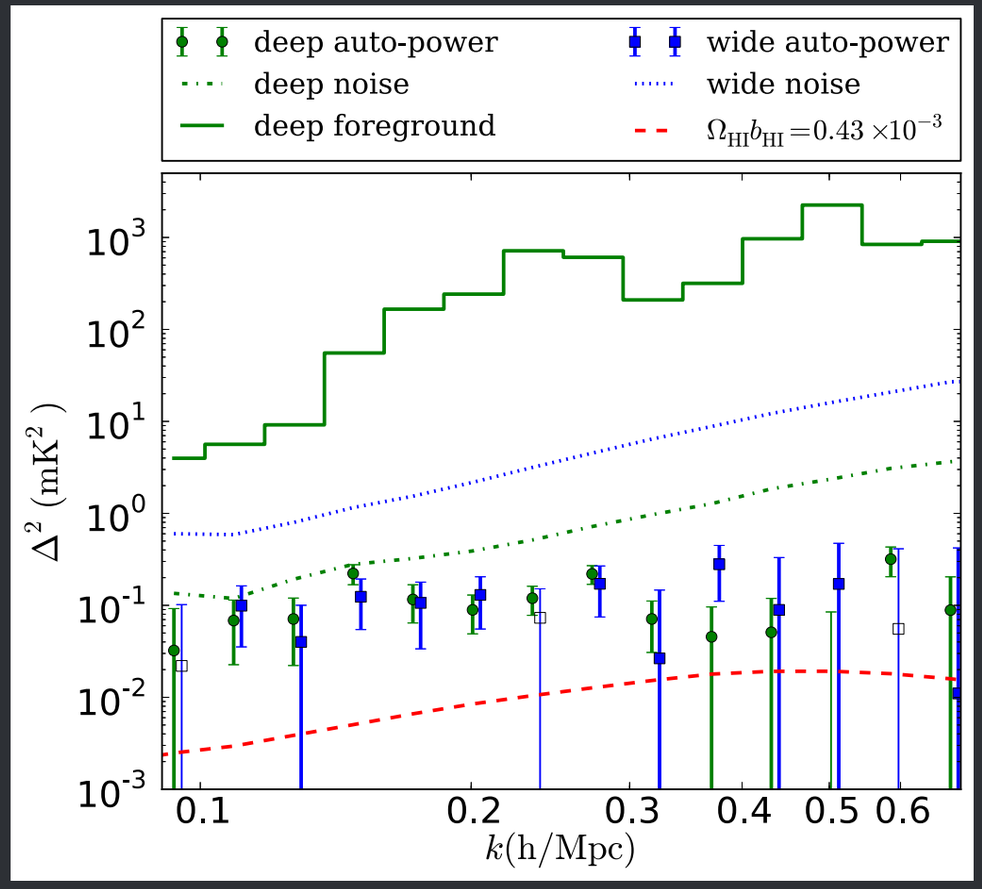
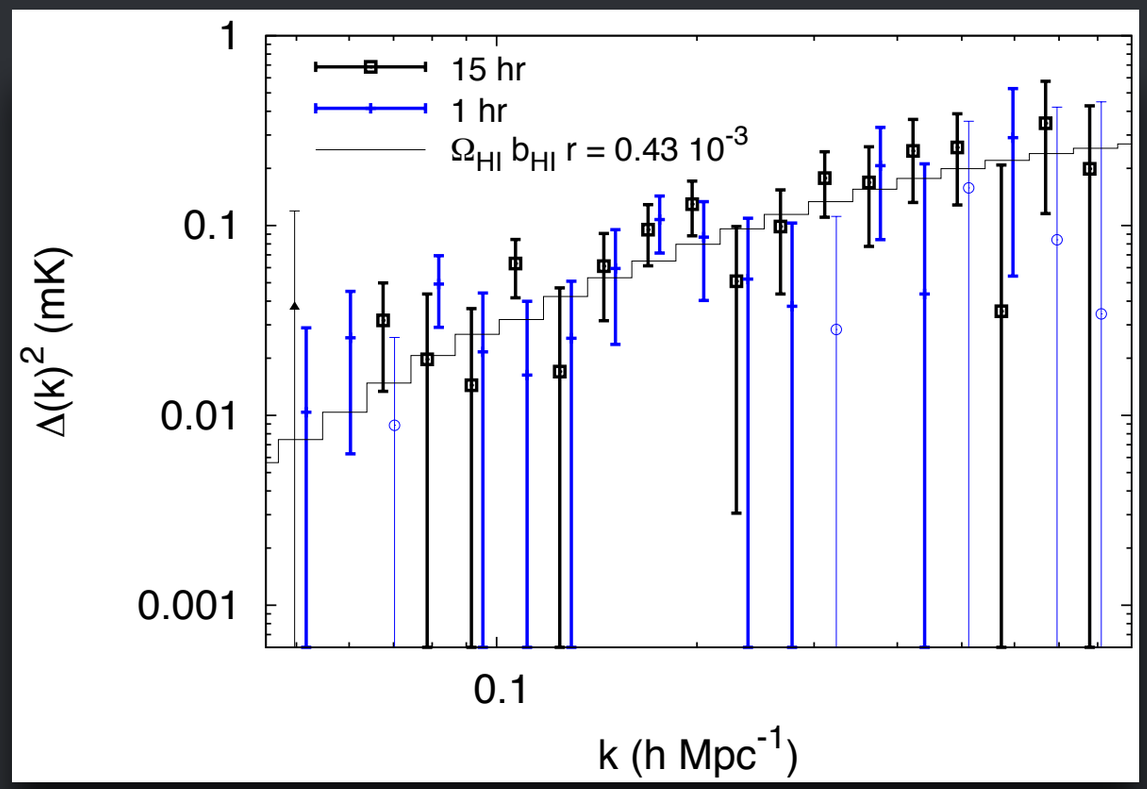
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 h^{-1} Mpc

- 200-hr HI survey of the WiggleZ fields at $0.6 < z < 1$
- HI cross-power and auto-limits in 2013 at z=0.8 implies:
- $\Omega_{HI}\, b_{HI} = [0.62\ ^{+0.23}\ _{-0.15}] \times 10^{-3}$

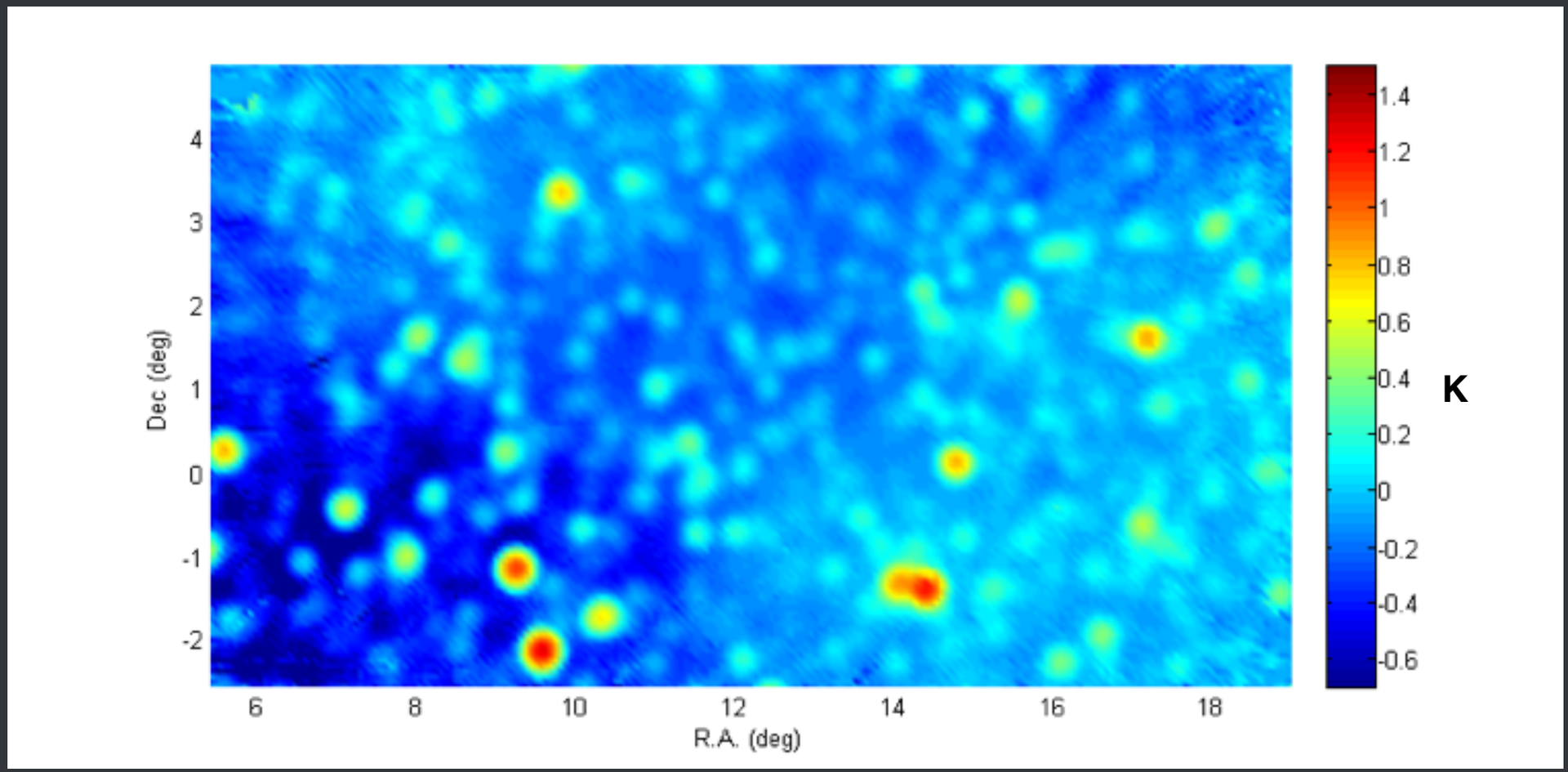


Auto-power limits, Switzer+13, GBT-HIM



Cross-power, Masui+ 13, GBT-HIM

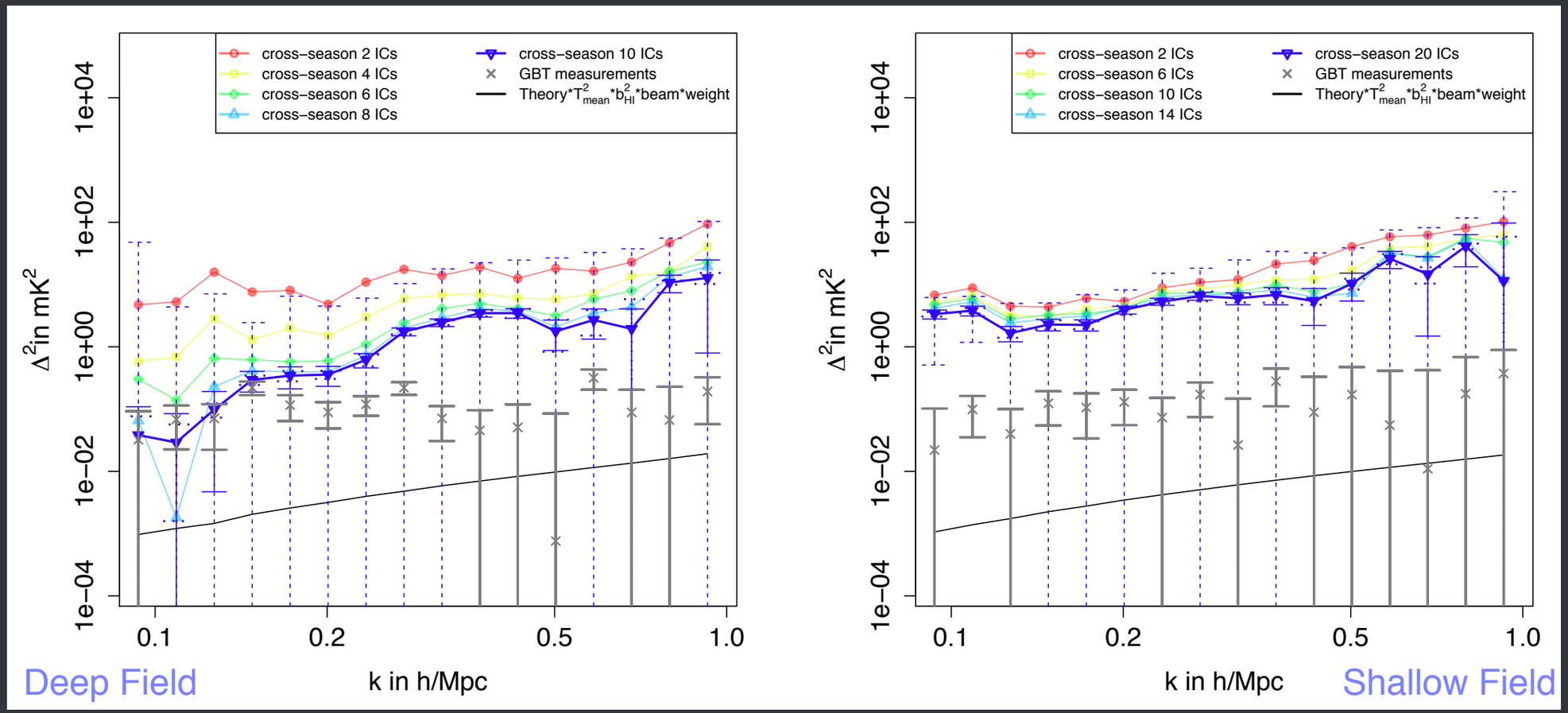
GBT-HIM Status Update



GBT WiggleZ 1hr field

- Analysis of ~800 hours of GBT observations
  - WiggleZ 1hr, 11hr, 15hr, 22hr fields
- Improve HI power spectrum limits
- Measure HI-optical cross-power RSD effects
- Focus on the 1hr field:
  - Alternative Foreground cleaning techniques
  - Polarization calibration improvement
  - Polarization leakage power spectrum estimates
  - Handling of residual ground-spill contamination

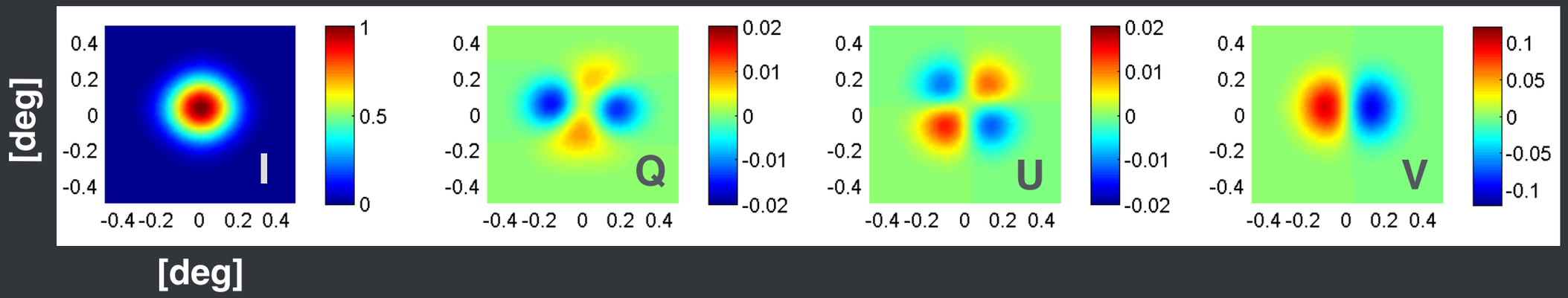
Foreground Mitigation: SVD v.s. ICA



Laura Wolz et al., +GBT-HIM team, 2016

- Foreground Projection/Subtraction Methods:
  - SVD - singular value decomposition: spectral and spatial eigenmodes (Switzer, Chang, Masui, Pen, Voytek 2015).
  - ICA - independent component analysis. FastICA (Wolz et al. 2014).
  - SVD: signal loss, compensated by calculating transfer functions.
  - ICA: no signal loss. But more difficulty in handling systematics.
  - ICAxICA, SVDxICA maps: no obvious improvement on the power spectrum limits

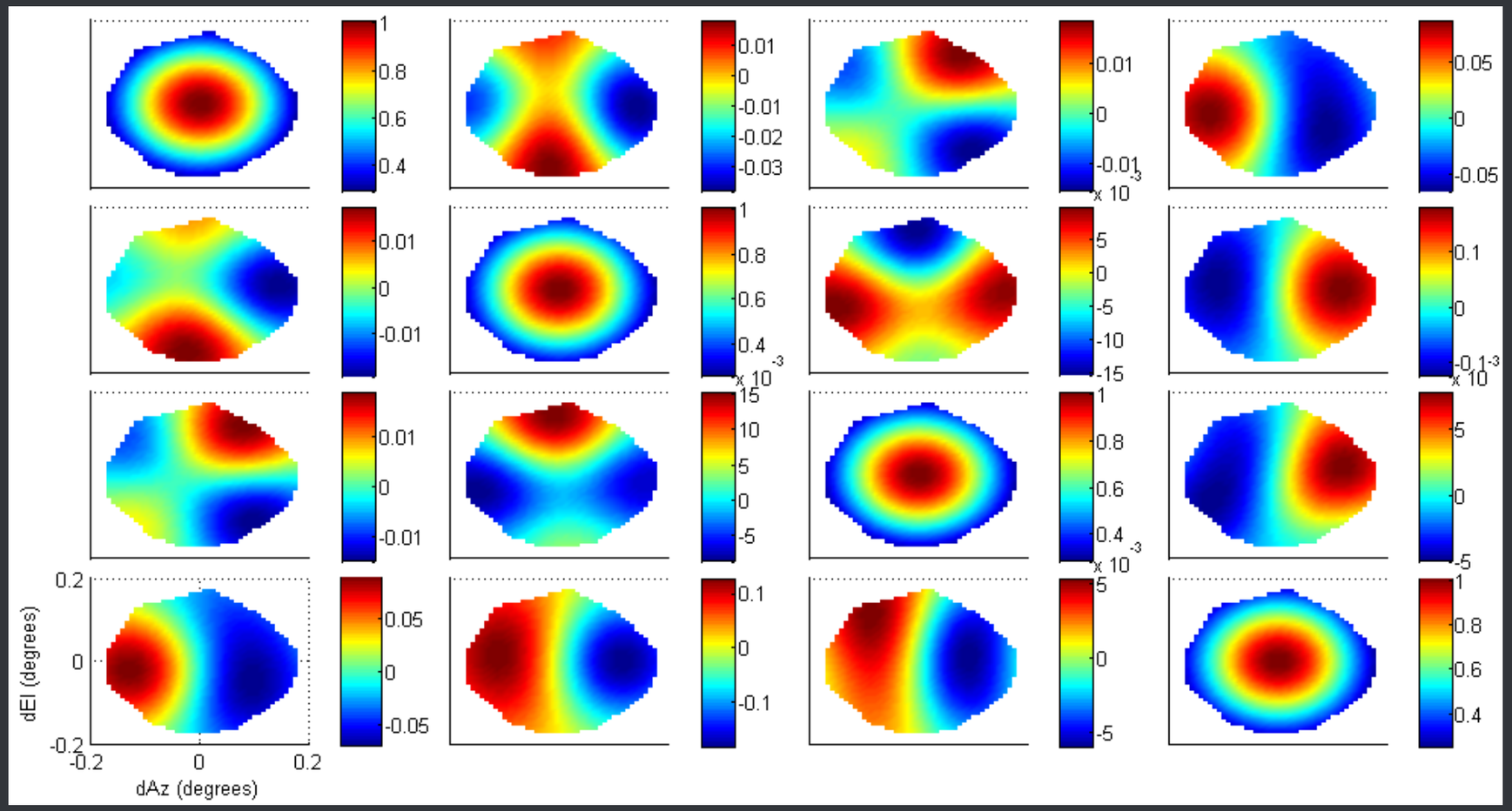
Precision polarization calibration at GBT



Liao, Chang et al., 2016

- Accurate characterization of GBT polarized beam patterns
  - Polarized foregrounds are ~100 times (in temperature) brighter than the expected HI signals.
  - Polarization leakage (P -> I) at the 1% level may contaminate HI signals.
  - Polarization leakage may introduce frequency structure to mimic the HI signals:
    - Faraday rotation in the atmosphere
    - Leakage may be frequency dependent

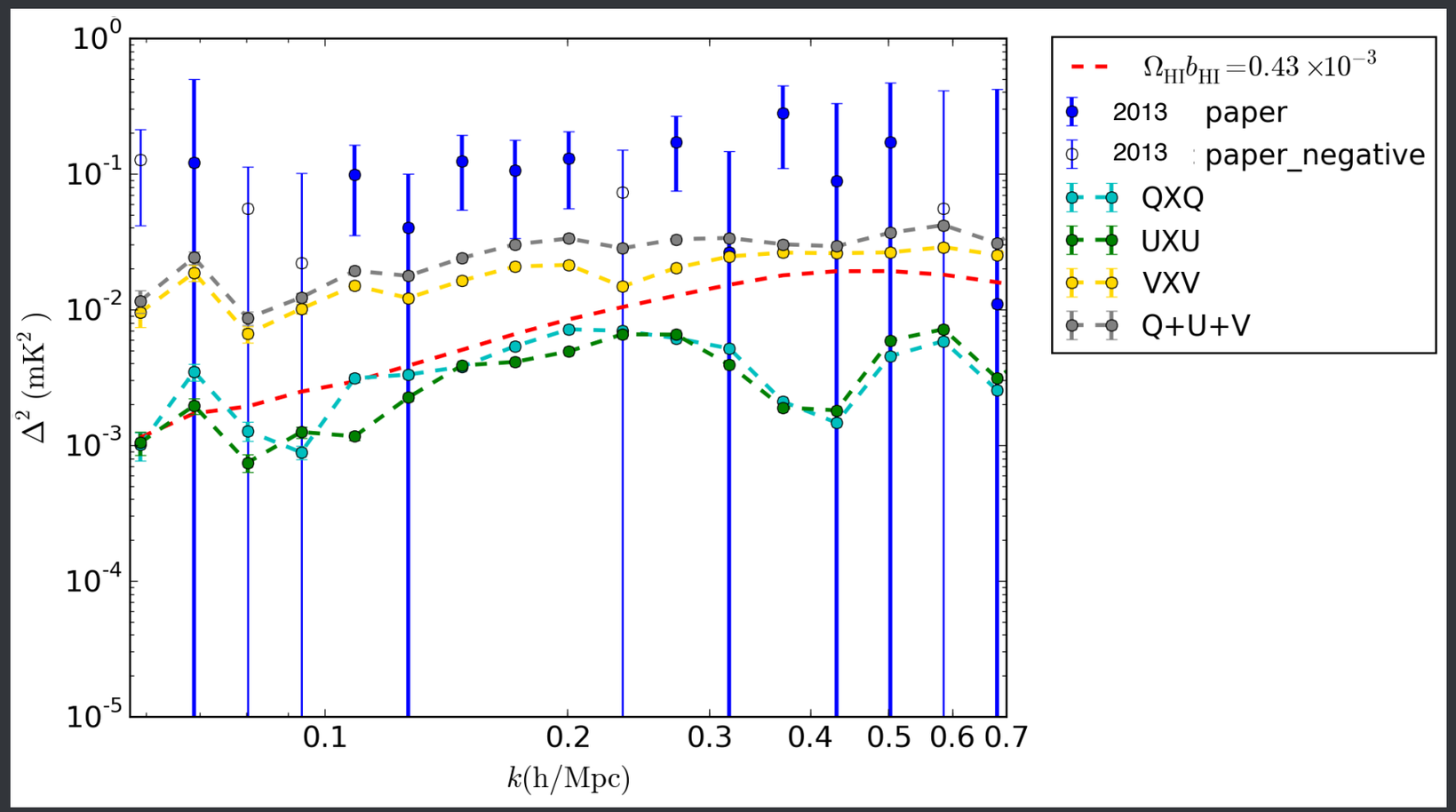
Precision polarization calibration at GBT

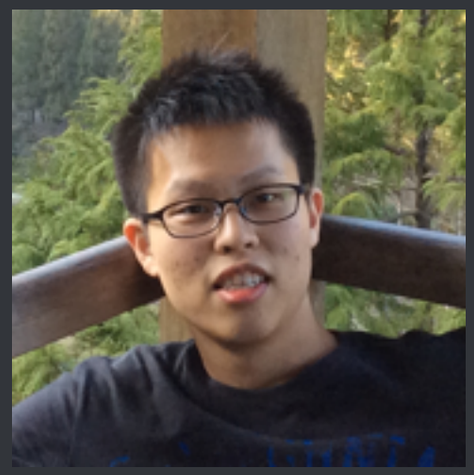


Liao, Chang et al., 2016

- GBT Mueller 4 x 4 beam
- $S' = J_B R_{\hat{v}}(\phi) S$
- Make use of quasars, pulsars and noise-diode (switching at 16 Hz) to constrain six-parameter Jones/Mueller matrix.
- Reached ~0.6% precision on-axis (boresight).
- Correct for ionospheric RM ~ 2 deg m^{-2}. Polarization angle rotation ~10-20 deg.

Leakage power spectrum estimate





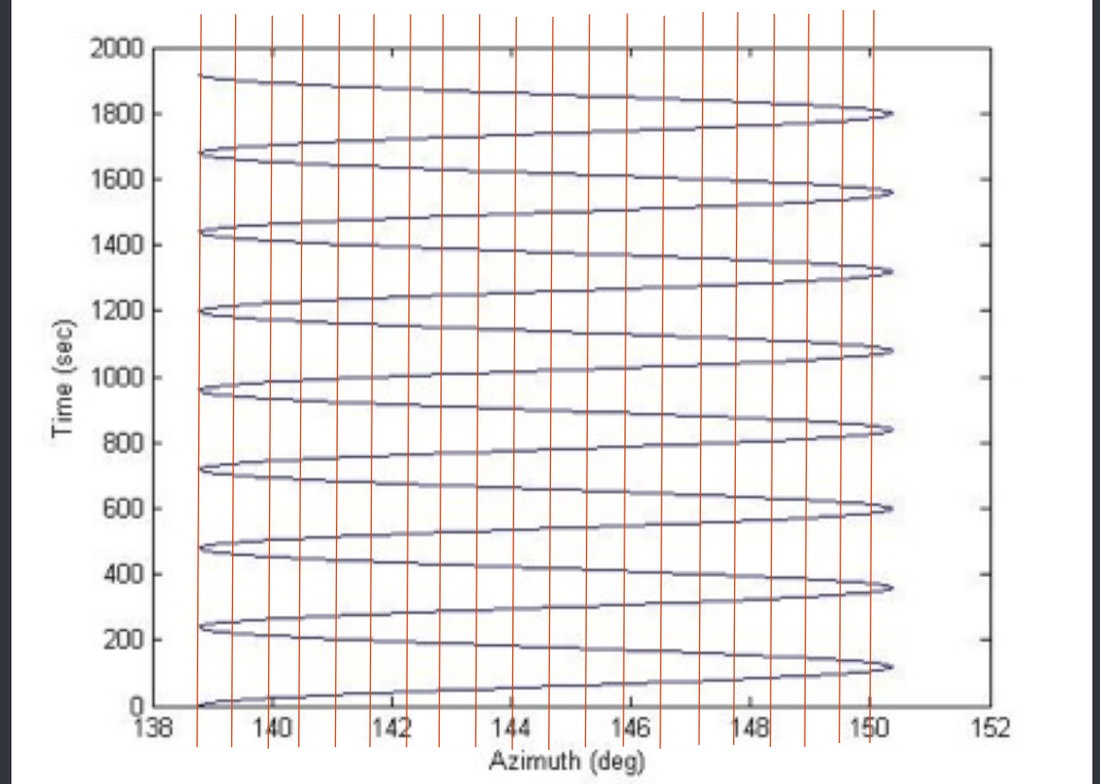
Chun-Hao To (Stanford)

To, Chang, GBT-HIM, in prep.

- Upper limits on leakage power spectrum contamination
  - Estimate (scan-averaged) pol-beam deconvolved maps, and calculate expected leakage.
  - Polarization leakage power spectra < 10% HI upper limits but can be10x expected HI signals; working on detailed simulations and error estimates
  - Incorporate full polarized beam model in map-making?

Residual Ground-spill maps

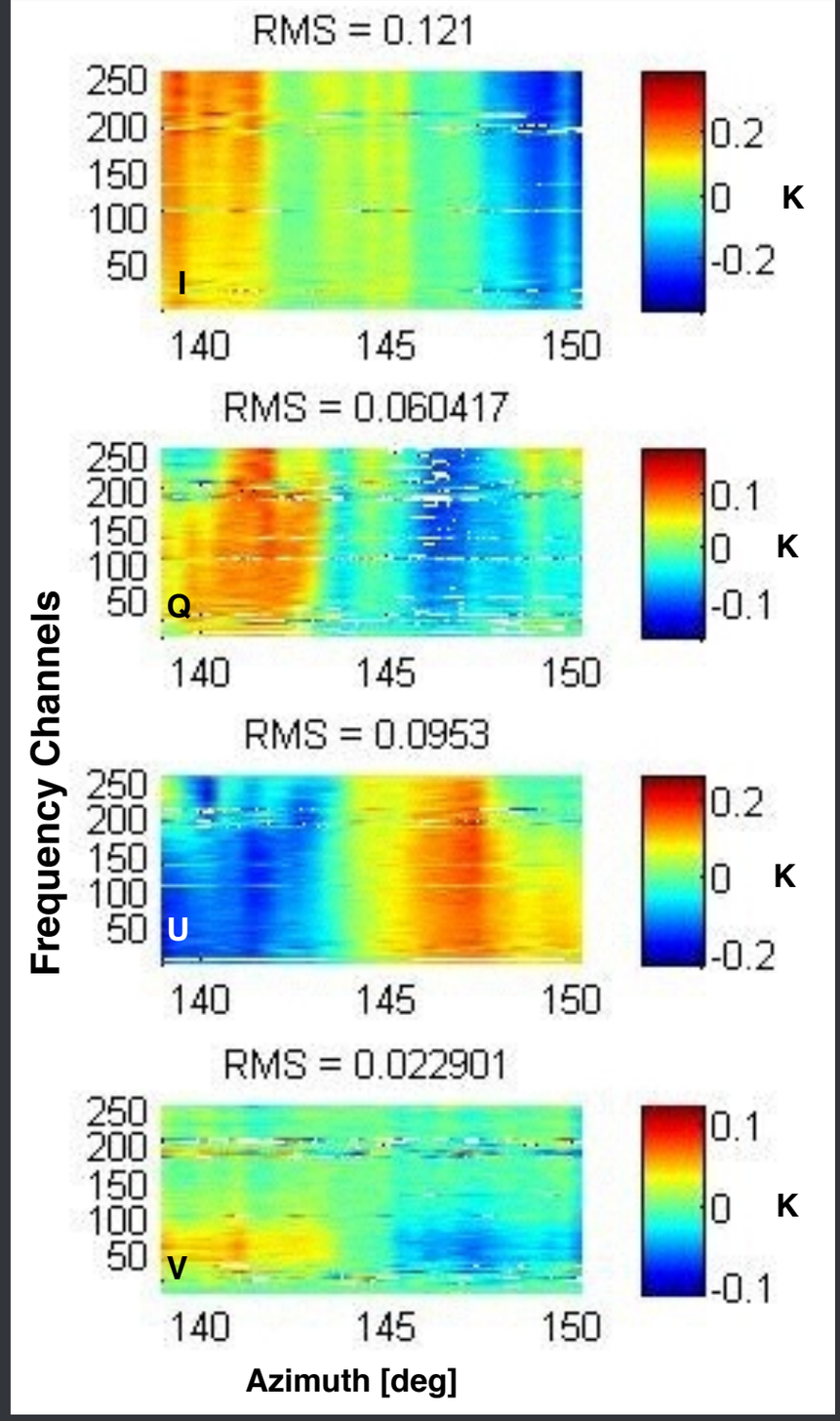
GBT scan strategy



- Residual ground spills that may contaminate P(k)

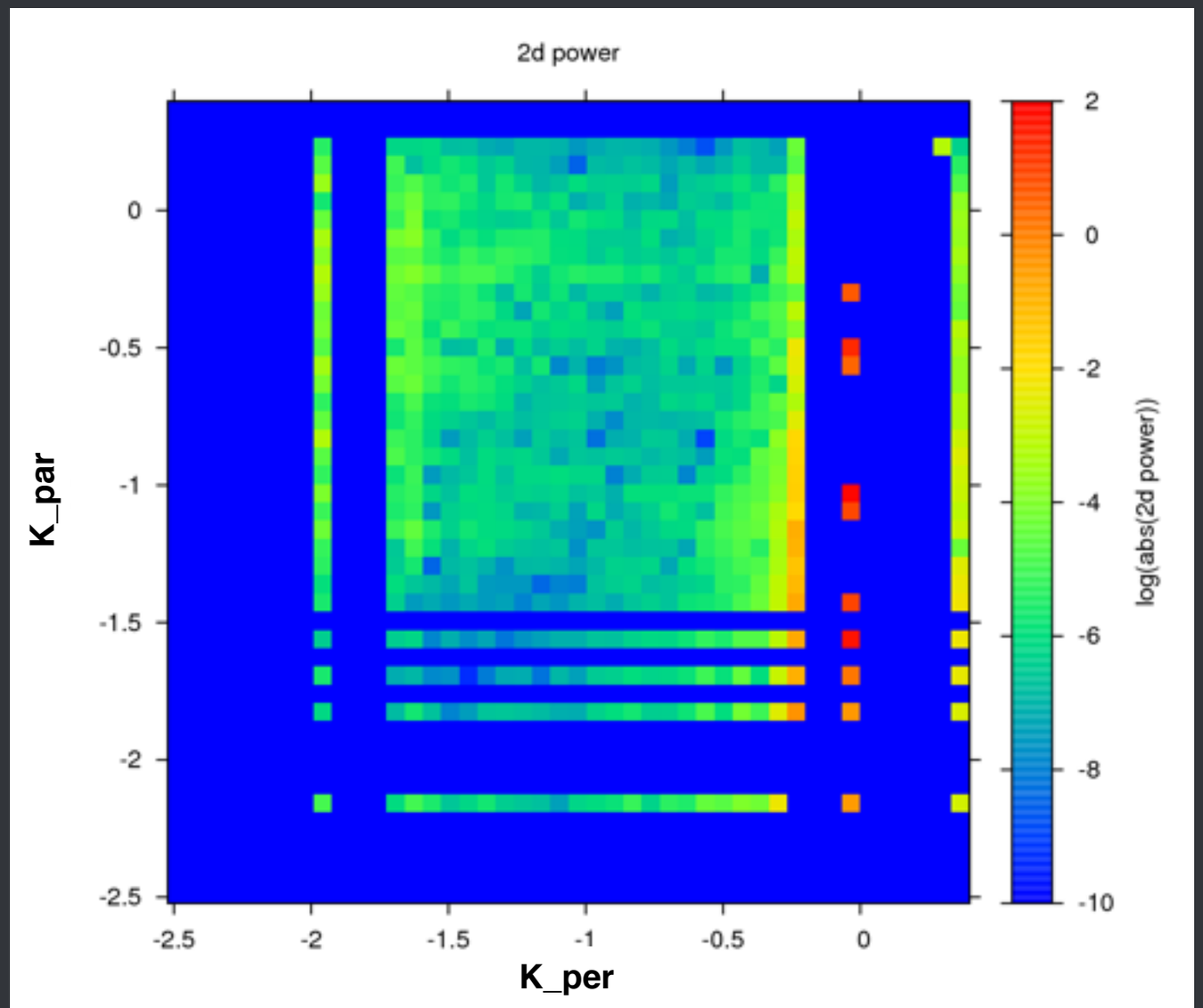
  - GBT scans at constant elevation. Mean and gradient per scan subtracted off to minimize ground spill contamination.
  - Examine residual ground maps in (azimuth, frequency).
  - Subtract 2 modes accounting for the residual grounds and incorporate the loss in the noise model.

GBT residual ground maps



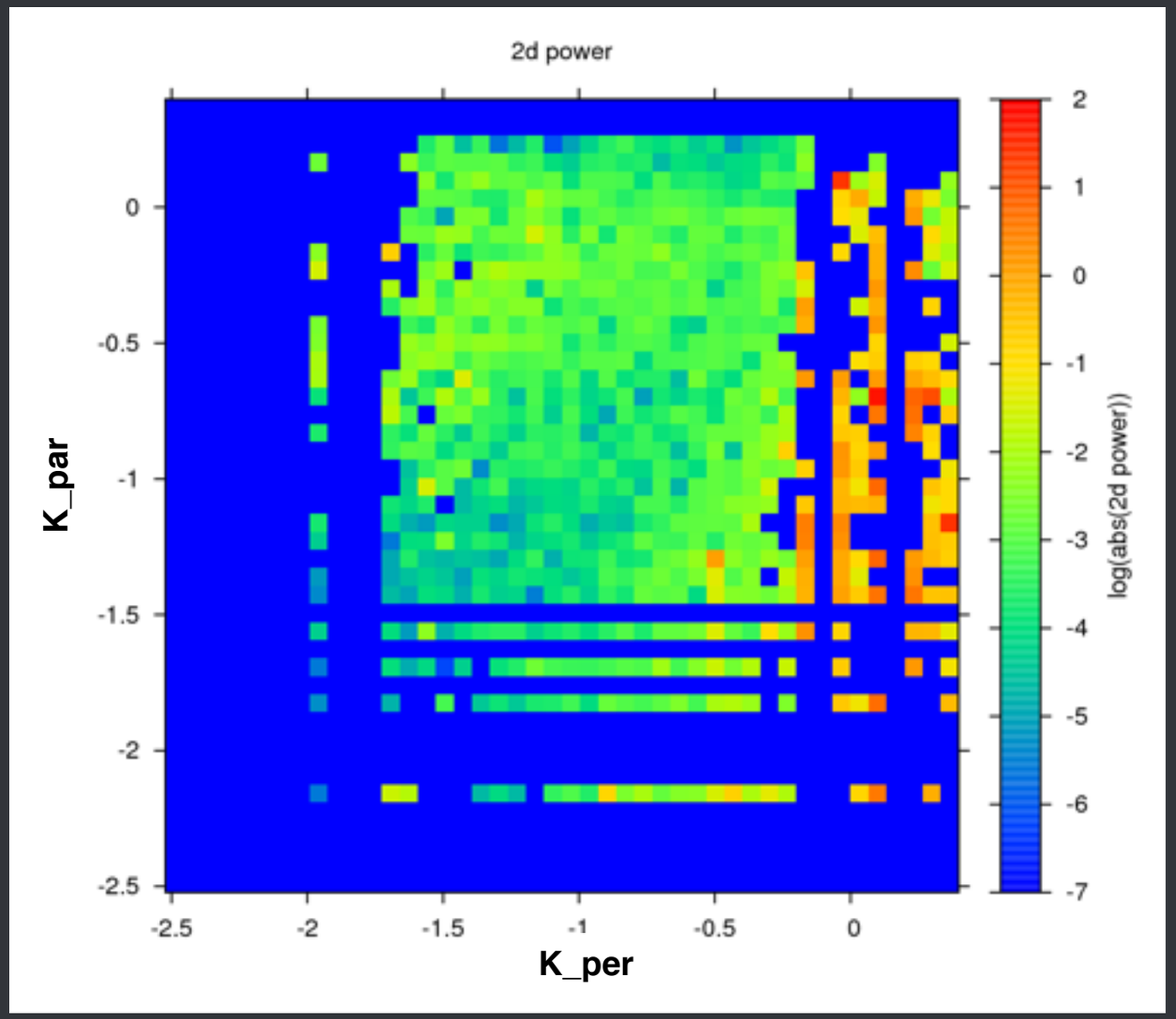
Liao, Chang et al., in prep.

Work in progress:
Updated HI auto-power spectrum at z~0.8



- HI power spectrum P(k)
  - Systematics dominated
  - Improved polarization calibration with full mueller matrix treatment
  - Including full polarized beam model in map-making (To-do)?
  - Incorporating full 3D covariance matrix calculation for optimal map-making (To-do) ?
  - Larger survey field enabling better foreground SVD subtraction

Work in progress:
Redshift-space distortions with cross-power spectrum



- Redshift-space distortion (RSD) measurement with HI-WiggleZ cross power spectra:

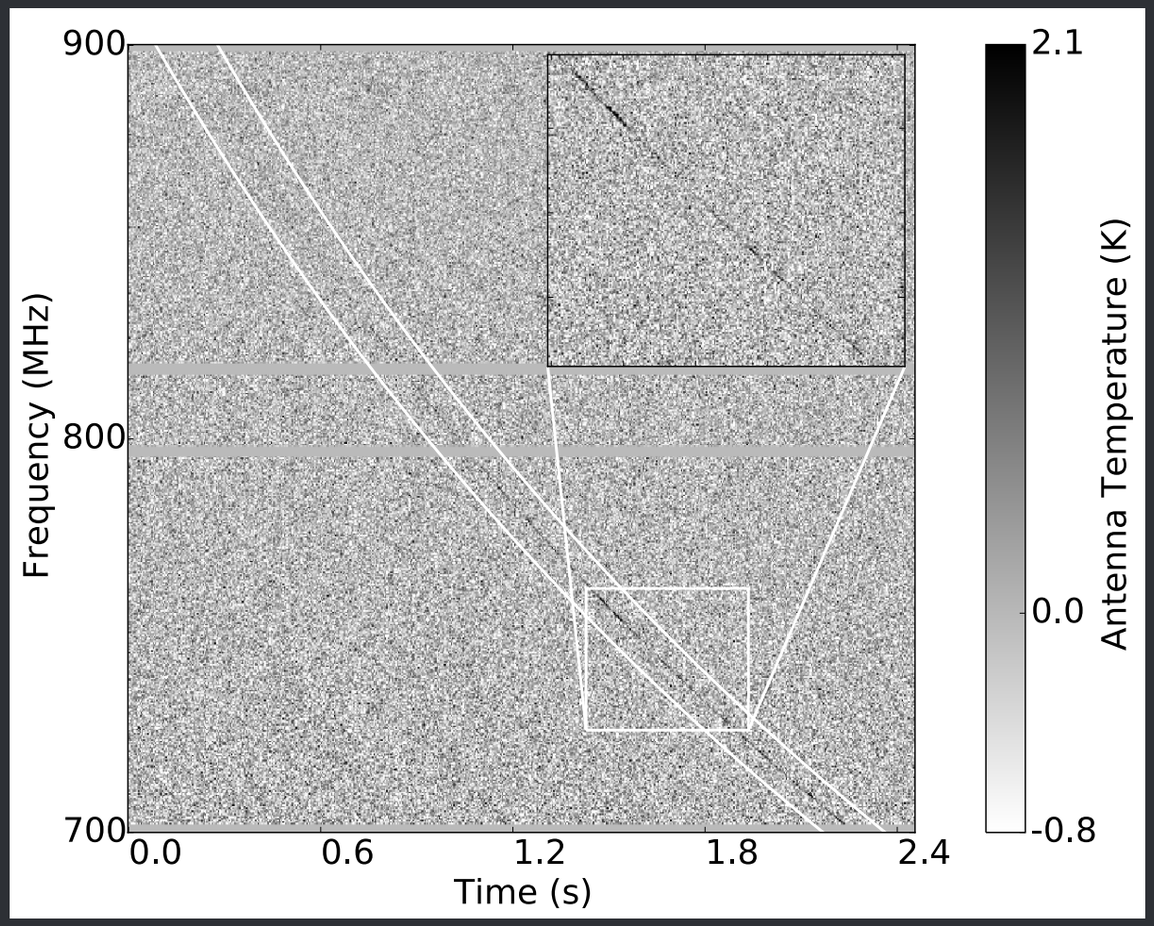
- Anisotropic clustering gives measurement of Ω_{HI} and b_{HI}

- Currently working on RSD modelling for HI intensity mapping; investigating effect of foregrounds on RSD interpretation.

- Hint of a "dipole" term? (c.f Bonvin+ 15).

- Improving cross-power spectra measurements

21cm Intensity Mapping at GBT: Fast Radio Burst (FRB) Found!

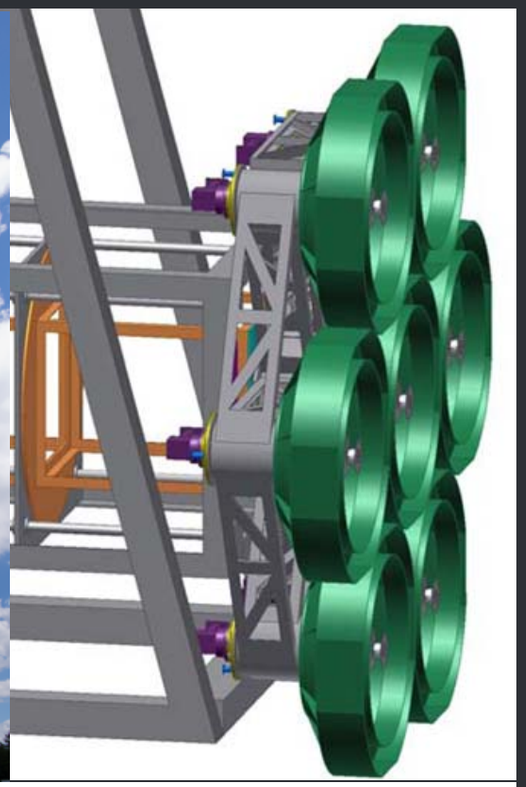


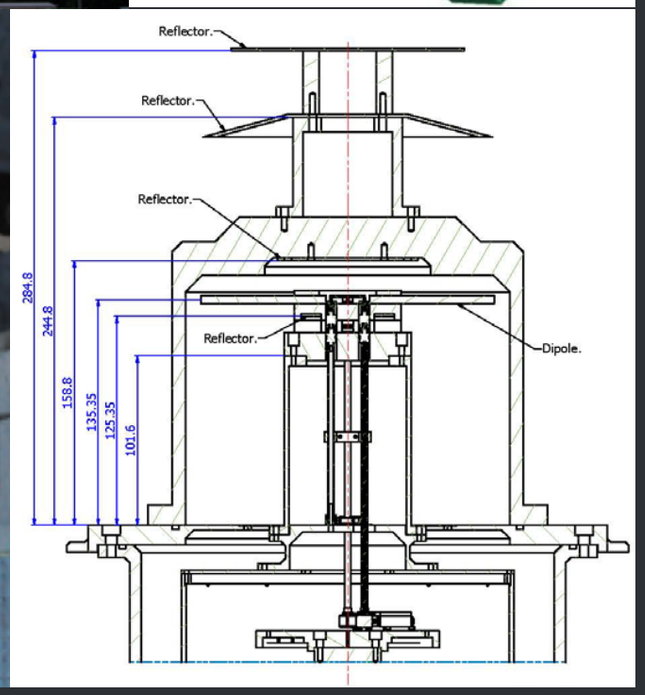
Masui et al., the GBT-IM team
2015, Nature

- FRBs are bright, millisecond radio flashes of unknown origin (Lorimer et al. 2007)
- We search through 700 hours of GBT HI data at 700-900 MHz, found one event
- First FRB detection under 1 GHz, with linear polarization (44%) and Faraday Rotation Measurements.
- DM = 623 pc cm^{-3}, RM = -186 rad m^{-2}
- The FRB detection implies a source location in the dense central region of its host galaxy, or the presence of magnetized material associated with the source itself.

GBT-HIM

21cm Intensity Mapping for BAO & RSD studies



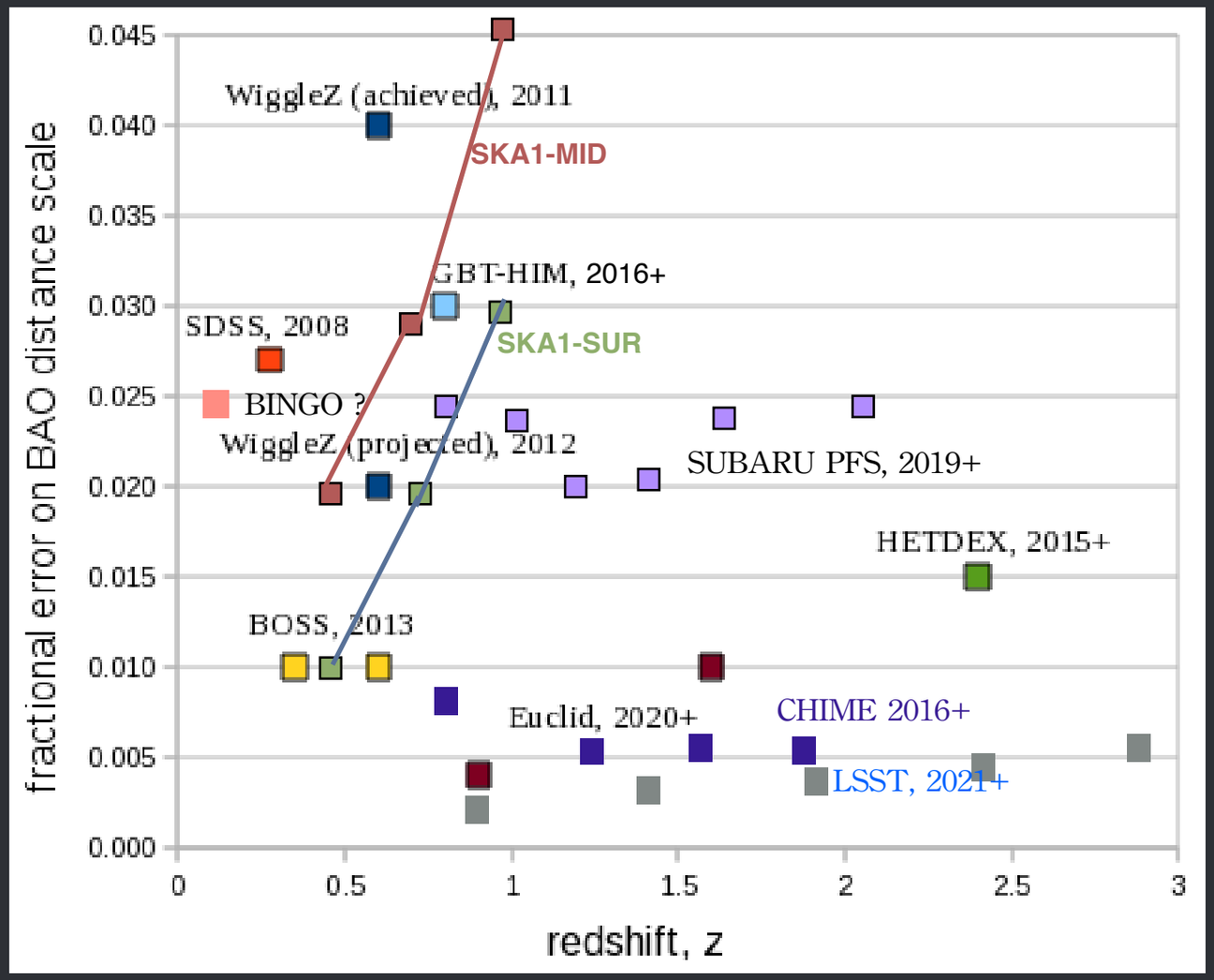


- GBT-HIM Project:
  - Building a 7-beam receiver at 700-900 MHz for redshifted HI survey at 0.6< z < 1 for BAO measurements.
- Use Short-backfire Antenna (SBA) with a edge-tapered reflector; with a cryogenic HDPE cover to reduce Tsys.
- Prototype tested on GBT in December 2014. Passed Design Review in October 2016.

PI: T.-C. Chang

BAO measurements

- Forecasts on Baryon Acoustic Oscillation (BAO) distance scale.
- But hopefully learn more from each and combinations of the data sets.



Summary

- Good progress in 21cm IM measurements at both low and high redshifts, but we need a detection soon! (~Early days of CMB?!)

- Existing facility explorations:

  - PAPER/LOFAR/MWA/GMRT-EoR: 21cm fluctuations upper limit of 23mK at z~8 (Ali et al 2015).

  - HERA/SKA1-LOW: next generation EoR experiments. In construction/planning.

  - GBT-HIM/Parkes-IM: Cross-power spectra measured. Upper limits on HI power spectra at z~0.8 and z~0.08

  - BINGO, CHIME, HIRAX, SKA1-MID, Tianlai: large-scale 21cm IM experiments. Constructed or in progress.

  - COPSS (SZA-CO): CO power spectra ~2.5-sigma measurement at z~2-3 (Keating et al. 2015, 2016).

  - SDSS: Lya IM in cross-correlation at z=2-3 from LRG spectra (Croft et al. 15).

- Cross-correlation sciences are extremely insightful/useful.

- Line intensity mapping on-going/planned programs: Time ([CII]), SPHEREx (Lya), LAMP (Ha), AIM-CO and COMAP (CO). Stay tuned!